A LOW COST PV PANEL ASSEMBLY TARGETED AT RURAL ENERGY SUPPLY IN DEVELOPING NATIONS

Philippa K Hardy*[1], Chandra S Malvi[1], Manoj K Gaur[2], Darron W Dixon-Hardy[1] and Rolf Crook[1]

[1]Energy and Resources Research Institute, School of Process Environmental and Materials Engineering, University of Leeds, UK

[2] Madhav Institute of Technology and Science, Gwalior, Madhya Pradesh, India.

***Corresponding author pre4pkh@leeds.ac.uk**

1. Abstract

There is a huge potential to utilise solar power in developing nations, however the expensive nature of solar panels is preventing this market growth at the local level. Widely available and low cost materials and methods are imperative for solar panel assembly for rural energy supply if the mass uptake of Photovoltaic (PV) in developing nations is to be realised. In this research a novel and inexpensive assembly for PV panels using commercial silicon PV cells was developed using alternative materials and techniques. The panels were subjected to laboratory testing in Leeds, UK and field testing in Gwalior, India. The materials used for the assembly were polyethylene terepthalate (PET), for encapsulating the solar cell, and polycarbonate (PC) sheet, for the facing and backing of the panel. The aim was to demonstrate that the cheaper encapsulation technique and materials do not affect solar panel efficiency compared to more common ethylene vinyl acetate (EVA) and glass fabricated panels and commercial solar panels. We are able to show that a solar panel assembled with PET and PC produces similar results in terms of power and efficiency to the standard assembly method using EVA and glass. As well as competing with current panel assembly the solar panels used in this research are cheap and simple to make, making them suitable for rural energy supply.

2. Introduction

Approximately 1.6 billion people in the world have no access to electricity and another 2 billion have limited supplies (UNEP 2008). Photovoltaic (PV) panel fabrication on a commercial scale is highly sophisticated, making use of expensive techniques and materials, where the complete panel packaging material and transport account for nearly half of the total panel cost (Jorgensen et al 2006). In order to incorporate solar cells into a fully functional panel, they have to be encapsulated and then protected with packaging. The packaging layers needed for an effective PV panel include a superstrate (front protective layer), an encapsulant surrounding the whole cell and a substrate (back protective layer) (Czanderna and Pern 1996). Vacuum lamination using Ethylene vinyl acetate (EVA) and glass is a well established method for assembling solar panels, however, EVA discolours over time and this technique is costly and not available to reproduce in remote or rural areas (Berman et al 1995; Pern and Glick 2000). The feasibility of using plastic materials in solar panels, in particular polyethylene-terephthalate (PET) and polycarbonate (PC), has been studied and indicated as a viable option (Hackmann et al 2004; Jorgensen et al 2006).

Here we present a simple, cheap and effective assembly for a solar panel suitable for rural energy supply, using a current commercially available silicon solar cell, PET and EVA as encapsulants, and PC and glass as substrates. The methods for securing the encapsulants around the cell simply involve using an office laminator and an iron respectively. The assembly provides a solar panel design that is competitive with existing PV panels where all of the materials used can be locally sourced in the UK and India and the methods for assembling the solar panels are simple to reproduce.

As well as providing an inexpensive solar panel, it is also important to ensure the life cycle emissions of the panels do not increase in order to mitigate climate change. Life cycle emissions of current commercially available solar panels are generally in the range of 30 gCO_{2e}/kWh (Alsema et al 2006a; Alsema et al 2006b), or higher depending on the study (Fthenakis et al 2008). It is well known that 50% of these emissions are due to the actual solar cell production, however the majority of the other 50% of life cycle emissions is attributed to the assembly materials and method employed (Fthenakis et al 2008; Alsema 2009). The proposed assembly method is anticipated to help reduce the life cycle emissions of solar panels, due to the utilisation of low energy techniques.

3. Method

3.1 Panel Assembly

We assemble three dissimilar panels to test our novel assembly against current assembly methods and to demonstrate that depending on material availability various assemblies can be produced. Three types of single cell panel are assembled using various mixtures of encapsulating materials (PET or EVA) and PC or glass for the facing and backing of the solar panel, shown in Figure 1.

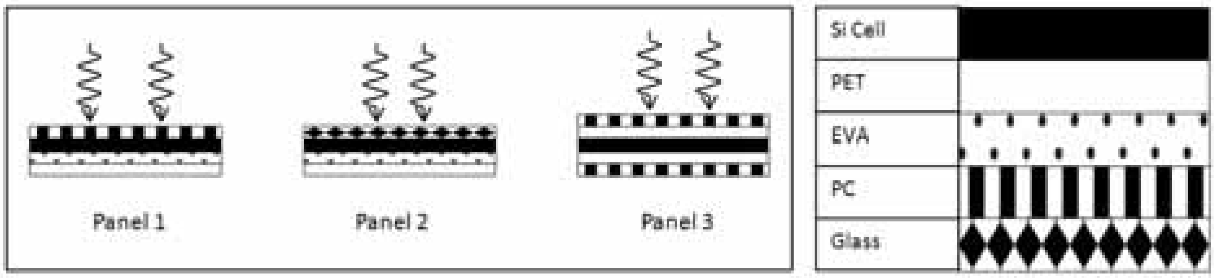

Figure 1: Schematic and key for all 3 different solar panel assemblies.

Initially electrical connections are established by soldering ribbon onto both sides of the cell and connecting them to an external wiring system. Encapsulation of the cell is accomplished by lamination of PET simply using an office laminator at 140°C or an iron to secure the EVA to the cell. Further packaging involved encasing the encapsulated cell into a final protective casing using glass or PC sheet of 2mm maximum thickness at the front of the cell and PC or PET at the rear. Various frames and sealants to finish the panel were used, as these weren't the main emphasis of the research and were deemed not to affect solar cell performance. This method is very similar to conventional vacuum and lamination process but here equipment and materials are readily available, inexpensive and can be carried out at home. For testing purposes only one cell solar panels were fabricated, however using the same approach the panels can be easily scaled up. This assembly technique also provides a cost effective to way to repair or replace solar panels on a larger scale. The solar cells used were monocrystalline silicon solar cells, the specification for which are summarised in Table 1.

Table 1: Monocrystalline silicon solar cell specification from Mars Rock Group (Mars Rock Group 2011).

Cell Dimensions	Length	125mm ± 0.5mm
	Width	125mm ± 0.5mm
I-V Characteristics	Short-circuit current	5.25A
	Open-circuit voltage	0.625V
Temperature Coefficient	Power	-0.119%/K
Efficiency related to Peak Power	Efficiency	Max Power
	16 – 17%	2.40-2.50 W

3.2 Outdoor Testing

Figure 2 shows the experimental set up for the panels. The solar panels fabricated as indicated in Figure 1 were securely mounted on to a wooden board, all with a ventilation gap at the back of the panel. The frame was tilted at 11.5° (the optimum summer angle for Gwalior, India), south facing, free from shadows and level. The three solar panels and pyranometer were connected to a circuit, described fully in (Hardy et al 2011), which was subsequently connected to a data acquisition unit with a USB connection to a computer, where current and voltage data could be collected constantly. We used Profilab expert software to run the data acquisition unit and collect the data. Data was collected simultaneously for all cells by ramping electronic loads for 1 minute and this was automatically scheduled to occur every 10 minutes. Each ramp collected approximately 60 current and 60 voltage corresponding data points; hence during a day 8640 data points were collected. This volume of data collection allows more reliable results. Data collection was affected by power cuts during outdoor testing hence some data is missing; however correlations between data points can still be made. The panels were cleaned daily to ensure optimum readings were obtained.

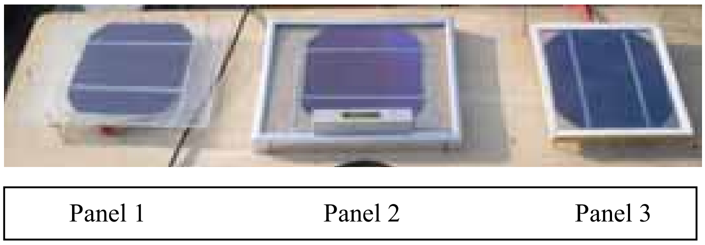

Figure 2: Experimental set up of solar panels.

Dust accumulation analysis on separate glass samples and yellowness testing of PET and PC samples were also undertaken. Samples were taken daily for a week and then weekly for 4 weeks to indicate the effect of dust on irradiance and possible degradation of the materials due to solar irradiance.

4. Results

5.1 Field Testing

All of the results below relate to 2 months worth of data collection between April and June 2011. The daily temperature and rainfall was recorded, as shown in Figure 3, to relate data collected with outside conditions. We can see from Figure 3 that the mean temperature was approximately constant at 35°C with the highest recorded temperature at 47°C and the lowest at 20°C. Generally no rainfall was recorded until the middle of June where there were 6 days of rainfall.

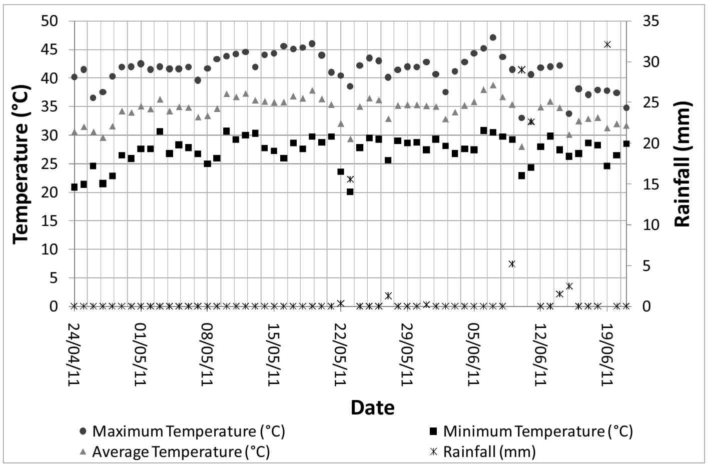

Figure 3: Record of temperature and rainfall for the experiment period 25/4/11-21/6/11.

From the data collected it was possible to analyse the I-V characteristics for each panel at any point throughout the day. Figure 4 shows an example of an I-V curve from the data collected. Comparing the I-V curves at peak irradiance (see Figure 5b) to the manufacturer’s specification for the cells in Table 1 shows a close correlation for all three panels. By analysing different ramps around midday we find a short-circuit current between 3.5-5A and an open-circuit voltage between 0.5-0.6V for the 3 panels. This indicates that all solar panels are achieving near to the actual short-circuit current and open-circuit voltage, despite being tested in real world conditions and not AM1.5.

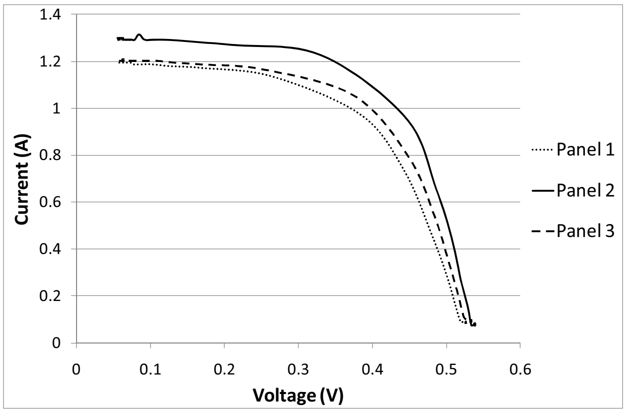

Figure 4: Example of an I-V curve for the 3 panels at 8am on 26/4/11.

From the I-V data collected peak power was calculated for each panel over each ramp as shown in Figure 5a. It is visible that panel 2 has the greatest peak power followed closely by panel 3 and then panel 1. Panel 3 uses the novel assembly of PET and PC around the solar cell hence indicating the success of the panel assembly in comparison to the other two panels. The data points below the observed mean for each panel could be due to shadows caused by clouds or some small error in the data collection. Figure 5b highlights that as anticipated the peak power for each panel directly links to the irradiance. As expected peak irradiance is around midday, sharply increasing from 8am and greatly decreasing from 3pm. The data underneath the mean irradiance curve could be due to shadows caused during the course of the day in the form of clouds.

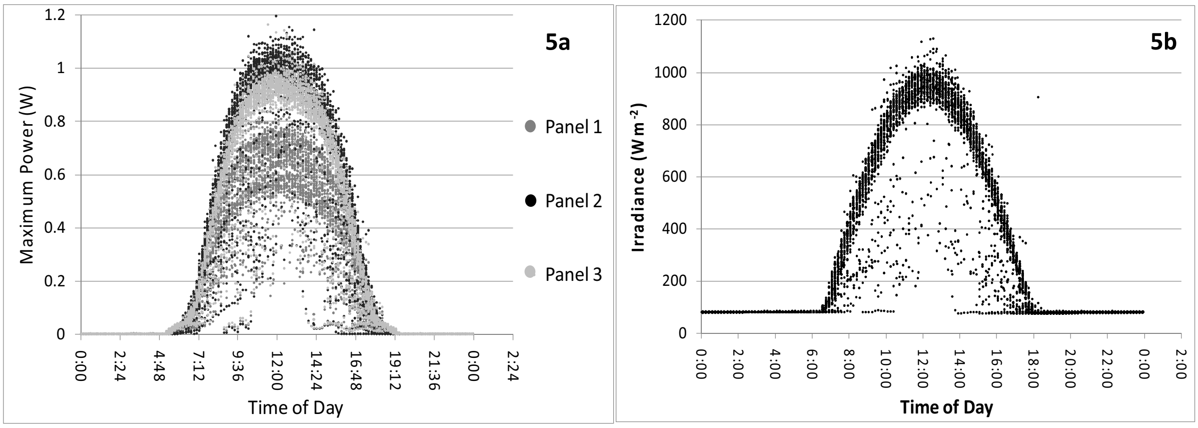

Figure 5: (LEFT: 5a) Peak Power over time of day for all 3 panels. (RIGHT: 5b) Corresponding average irradiance data per ramp related to time of day.

Using the peak power points for each ramp and each panel the energy and efficiency were then calculated. Figure 6 shows the efficiency of all 3 panels related to time of day, showing the highest efficiency gained to be 10% by panel 2 and the lowest efficiency of around 4% from panel 1. Panel 3 has efficiency values similar to panel 2, in the range of 6-7.5%. The affect of high temperatures on the cells is evident from Figure 6 where a dip in efficiency of all 3 panels occurs during the peak irradiance hours of the day. We expect the power of the cell to drop by -0.119%/K after 25°C as indicated in Table 1, this correlates with the observed dip since temperatures reach highs of 47°C with the actual solar cell temperature expected to increase further. The maximum efficiency of the panels occurs during the late morning and afternoon when irradiance is not at a maximum, agreeing further with the temperature effect on cell efficiency. This may also help explain why the panels do not gain the same power output as stated in the specification for the cells.

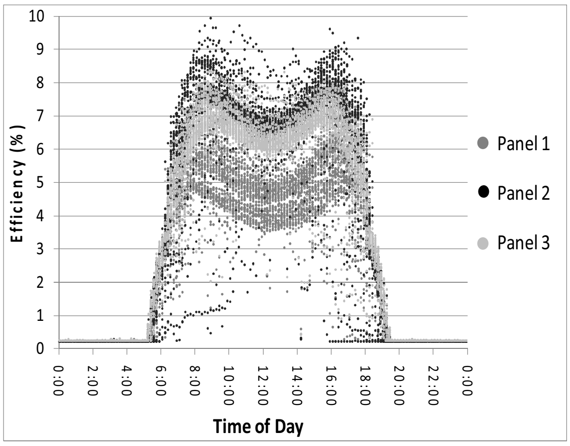

Figure 6: Efficiency of the panels against the time of day.

Further analysis of energy and efficiency on a daily basis is shown in Figure 7. The energy of the panels correlates well with maximum irradiance per day, highlighted in Figure 7a since when daily irradiance is higher, so is the energy from the panels and vice versa, emphasised on 08/05/11 and 18/05/11 for example. A general trend across all points is visible however panel 1 appears to not only have a decreased energy in comparison to the other panels but it also appears to be degrading slightly over time. Figure 7b shows a similar trend with the efficiency of all panels and it is more evident in this plot that panel 1 seems to be degrading over time. Analysing the difference between the efficiency of panels 1 and 2 in Figure 7b at the start and end of data collection we can see a difference of 1.6% and 2.2% respectively, supporting the idea that panel 1 is degrading with time. Unlike panel 1, panels 2 and 3 maintain a good daily efficiency, correlating well with irradiance and each other. Despite the cleaning regime all panels seems to slightly recuperate in efficiency after the rainy days in mid to late June. It is noteworthy to highlight that the gaps and few data points that sit outside of the general trend in the daily data here indicate where the experiment was affected by power cuts.

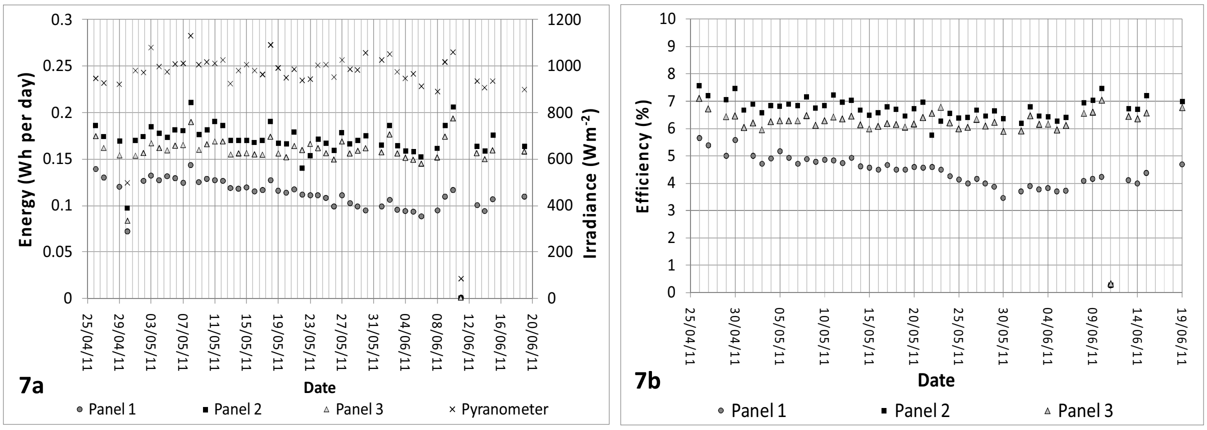

Figure 7: (LEFT: 7a) Energy from each panel per day, inclusive of maximum daily irradiance data. (RIGHT: 7b) Panel efficiency per day (the plot here uses maximum power and maximum irradiance to calculate efficiency).

The peak power and efficiency for the better performing panel, panel 2, gives a peak power of 1W (in Figure 5) and a peak efficiency of around 7% (in Figure 7), these correlate with the specification of the solar cell as shown in Table 1, but are half the amount.

5. Discussion

It is evident from the results that the best performing panel was panel 2, closely followed by panel 3 (the fully plastic assembly) and significantly below these is panel 1. The difference between panel 1 and 2 in all of the results is a considerably large fractional difference of approximately 0.5. There are many explanations that could account for this including the actual silicon solar cells having different efficiencies, the encapsulation techniques used being insufficient, or some error having occurred in the circuit. The solar cells used can only vary in efficiency between 16-17% (see manufacturer's specification) this can therefore only account for a possible fractional error of 0.03 which is not large enough to explain the large differences observed. Likewise any possible error in the circuit would only account for a small fractional error. Together these values cannot account for the large fractional difference found in the results.

Possible explanations to account for the fractional difference between panel 1 and the other 2 panels could be explained by the cell encapsulation, material degradation or panel assembly. The PC used in panels 1 and 3 is UV protected (confirmed by UV-Vis spectrometer testing) and so it can be concluded that neither panel was subject to UV degradation. The panel temperatures would have exceeded the measured temperatures shown in Figure 3, manual monitoring of the panels found the panel surface temperature to peak at 56°C, however the temperature of the actual solar cell was not measured but is very likely to be considerably higher than this. In relation to this the PC could not have degraded with the temperatures experienced as it has an upper working temperature of 130°C (Hackmann et al 2004; Dynalab Corp 2011). There is a significant difference in assembly between panels 1 and 3 (the two panels that incorporated PC) which is the inclusion of a PET layer and air between the cell and the PC in panel 3, whereas panel 1 has no extra layer between the cell and the PC and is airtight. Therefore it is likely that the presence of PET is forming a protective barrier against either high temperatures, humidity or chemical attack that would otherwise degrade either the cell or the PC.

Collectively the results highlight that the panels have not achieved the efficiency that the solar cells are capable of. The results indicate a fractional difference of over 0.5 between the solar cell specification and the actual results for the solar panels. It is known that solar cell efficiency decreases with temperature (Radziemska et al 2003; Singh et al 2008). This temperature effect is evident in the calculated efficiencies shown in Figure 6, where at high irradiance efficiency significantly drops. The peak temperatures experienced in India were very high and as discussed above, the solar cell temperature is expected to be considerably higher. The other factor that can account for the large overall drop in efficiency could be due to the experimental set up. Low resistance wires of 1m were used to connect the solar panels to the circuit, however it is now thought that these wires could have affected data measurements considerably due to a voltage drop. This can be observed through shallower I-V curves found at higher irradiance throughout the data set. Future work will explore more sophisticated techniques for data collection.

Calculated energy and efficiency of the panels generally follows a downward trend which is directly related to the irradiance, but this may also be affected by dust covering. It is clear from UV Vis spectrometer data (not presented here) of dust accumulated on separate samples that dust does greatly affect the amount of visible light that can reach the cell. Furthermore it is suggested in the results that rain increases the efficiency which we can assume provides some extra cleaning of dust particles that the manual cleaning did not sufficiently remove.

6. Conclusion

We have successfully demonstrated a low cost and simple solar panel assembly method using PET, PC and currently available monocrystalline silicon solar cells. We achieve similar results between the plastic solar panel and the more common glass and EVA solar panel suggesting that a plastic panel is a feasible alternative. The PET is also found to provide some sort of protective function to the cell, since the results show that the panel without a protective layer between the PC and cell did not perform as well as the other panels.

We use readily available materials and equipment and simple lamination techniques including the use of an office laminator. The cost for the assembly materials for a 1 cell solar panel in India was found to be between €2 for the PC/PET assembly and €4 for the glass/EVA assembly. With mass production this cost will greatly decrease. Further work includes continuing analysis on the degradation of this assembly to ensure that it is feasible for long term use as well as experimenting with various other assembly methods.

7. Acknowledgements

The authors from Leeds would like to thank the staff at Madhav Institute of Technology and Science (MITS), Gwalior, India, for kindly allowing the experimental work to be carried out at their institution, using their facilities and providing assistance. The authors would like to thank EPSRC, WUN-FIRC and the Government of India for funding support.

8. References

Alsema (2009). Life-cycle assessment of crystalline silicon PV module production by REC. 24th European Photovoltaic Solar Energy Conference,. Hamburg, Germany,.

Alsema et al (2006a). Environmental Impacts of Crystalline Silicon Photovoltaic Module Production. 13th CIRP

Intern. Conf. on Life Cycle Engineering,. Leuven, .

Alsema et al (2006b). Environmental impacts of PV electricity generation - a critical comparison of energy supply options. 21st European Photovoltaic Solar Energy Conference,. Dresden,Germany,.

Berman et al (1995). "EVA laminate browning after 5 years in a grid-connected, mirror-assisted, photovoltaic system in the Negev desert:effect on module efficiency." Solar Energy Materials and Solar Cells 36: 421-432.

Czanderna and Pern (1996). "Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review." Solar Energy Materials and Solar Cells 43: 101-181.

Dynalab Corp. (2011). "Plastic Properties of Polycarbonate (PC) " Retrieved 07/08/11, from http://www.dynalabcorp.com/technical_info_polycarbonate.asp.

Fthenakis et al (2008). "Emissions from Photovoltaic Life Cycles." Environmental Science & Technology 42(6): 2168-2174.

Hackmann et al (2004). "Technical feasibility study on polycarbonate solar panels." Solar Energy Materials & Solar Cells 84: 105-115.

Hardy et al (2011). "A scalable low-cost USB-powered circuit for I-V characterisation of single PV cells." [In preparation].

Jorgensen et al (2006). "Moisture transport, adhesion, and corrosion protection of PV module packaging materials." Solar Energy Materials and Solar Cells 90(16): 2739-2775.

Mars Rock Group. (2011). "Mars Rock." from http://marsrock.en.alibaba.com.

Pern and Glick (2000). "Photothermal stability of encapsulated Si solar cells and encapsulation materials upon accelerated exposures." Solar Energy Materials & Solar Cells 61: 153-188.

Radziemska et al (2003). "The effect of temperature on the power drop in crystalline silicon solar cells." Renewable Energy 28(1): 1-12.

Singh et al (2008). "Temperature dependence of I-V characteristics and performance parameters of silicon solar cell." Solar Energy Materials and Solar Cells 92(12): 1611-1616.

UNEP (2008). Reforming Energy Subsidies: Opportunities to Contribute to the Climate Change Agenda.